Near-net-shape thermoplastic preforming with continuously automated cutting and robotic pick & place processes

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Abstract

Today's automated production lines for carbon fiber reinforced thermoplastic (CFRTP) parts of the aerospace industry are mostly designed for one special part or application. Changing part geometry or material would lead to a complete re-design of the whole process chain. Here comes the flexible and highly automated the DLR process into game: A continuously automated production line "from fabric delivery to the near net shape pre-form – ready for consolidation". With the paper and presentation, the authors would like to contribute to the industry's increasing needs of continuously automated but highly flexible process chains for variable high volume CFRTP parts.

Keywords: CFRTP, Preforming, draping simulation, forming simulation, near net shape, nesting, cutting, robotics, pick and place, ultrasonic welding, automation

1. Motivation

In modern helicopter industry production rates for one model typically vary from 50 to rarely 100 helicopters per year. Considering such low production rates it is mostly not possible to justify an extensive invest in automated production lines. The degree of capacity utilization of such lines, being specialized on the production of one single part, hardly can be shown.

The same applies for aircraft manufacturers with a high part variety, such as e.g. the so called A350 clips, where more than 2500 different clip designs among 5000 clips exist. These designs can differ e.g. in the outer contour, laminate thickness, stacking sequence matrix material, folding angles or foot radii.

In contrast to existing, costly production lines and with respect to the above mentioned industry's needs DLR invented a highly flexible and continuously automated process chain "from fabric delivery to the tailored preform" with comparably low invest.

2. Production engineering

Prior to the "first ply cut", cut piece geometries as well as pick (in 2D), drop and weld positions (in 3D) for the cut-pieces to be laid down have to be defined.

Draping and forming simulations

In order to get a near-net part shape the single cut-pieces making up its laminate have to comply with this near net shape. As the cut-pieces usually are cut out of flat (e.g. rolled out) fabrics, the manufacturing engineering has to consider the draping of the cut-pieces from two to three dimensions. Therefor the authors used draping simulations in *Dassault's CATIA R23 Composites Part Design (CPD)* with a kinematic approach in case of low deformation degrees, which cause only low stresses during draping (comparable to a manual draping process).

Hereby the flexibility of the later described lay down process allowed the engineering to optimize the part by its performance and not restricting it for a better producibility (demonstrator part for draping by gripper and vacuum bag with performance optimized ply endings see Fig. 1). The near-net shape was generated by using the flattening and geometry transfer functions, which consider the internal kinematic mesh used for draping.

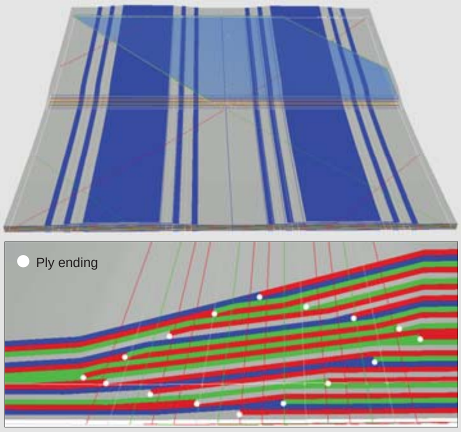

Fig. 1: Draping simulation of a 45° cut-piece of a fuselage skin preform (A350 curvature radius) out of CF/PES UD tape (top). Tooling surface (green) reconstructed out of laser measurement. Diamond shaped ply endings from thicker to thinner laminate region (bottom).

When expecting comparably high deformation degrees the authors used forming simulations in *ESI's Pam-Form 2015* based on finite element analysis, and therefore considering high stresses in the preform, as e.g. occurring in a forced forming process applied by two moulds in a press (demonstrator part for forming in a press see Fig. 2):

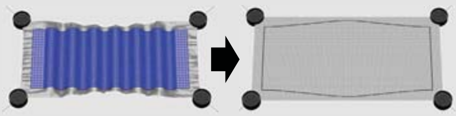

Fig. 2: Deformed preform (wave beam web) with tooling (blue) in forming simulation (left) and recalculated net shape (black) of the tooling edge on the flat preform prior to the forming process (right).

Here the near net shape was generated by projecting the near-net part shape on the formed organo sheet and then recalculating its undeformed shape. After-wards butt straps were added in *CATIA Generative Shape Design (GSD)* and the new geometry was again formed and iteratively recalculated. Tests showed that after three iterative steps a satisfying near-net shape can be generated.

Material efficient nestings

The thus generated near-net-shaped cut-pieces were then imported into the cutting software GTK Cut where they were nested with the nesting algorithm *AutoNesterT* from *Fraunhofer SCAI*. This nesting algorithm originally was developed for furniture and clothing industries. Tests showed that it is possible to increase the material efficiency by 10% and more when choosing a fiber-angle-suited cut-piece shape (fragmentation) and nesting and cutting several preforms at once. Considering this, material utilization degrees of up to 95% could be shown (see Fig. 3):

Fig. 3: Nesting for a skin part preform out of sliced UD layers, material utilization degree ≈ 95%.

3. Automated cutting process

Once the cut piece geometries are defined and nested, this information can be sent to DLR's automated cutting center consisting of a fabric roll storage, from which the fabrics automatically are brought to a feeder unit, which supplies a digital cutter, where the nestings are cut out, a pick unit, which picks the cut-pieces from the cutter table and lays them down in a drawer storage, in which the cut-pieces are brought to a robot cell (see Fig. 4). The utilized fabrics can be rolled goods like UD-Tapes, NCFs, wovens, fleeces and foils or even sheet goods like consolidated organo sheets.

Fig. 4: DLR's cutting center with movable drawer storage system.

Automated handling of cut-pieces on cutter table and lay-down in drawer storage

Because the surface of the cutter is limited, cut pieces have to be physically removed from the cutting table at certain times in order to allow ongoing processing. To automate the cut-piece handling a 4 degrees of freedom (DOF) axes portal kinematic with a gripping unit is installed above the cutter table. The manipulator is equipped with 432 electrically powered vacuum grippers which can be controlled independently.

Cut-pieces are removed from the cutter surface by lowering the gripping unit on the cut-pieces. Only the vacuum grippers covering the surfaces of the desired cut-pieces get switched on, applying adhesive forces between grippers and cut-pieces. By lifting the gripping unit the cut-pieces get separated from the remaining waste and can be placed in a drawer storage for further processing. Once all cut-pieces are removed, waste gets disposed into a recycling box placed in front of the cutter by moving the cutter's conveyor belt forward.

To fulfill todays requirements of a fully automated, flexible and reliable production process, a software solution had to be developed that generates optimal control commands for both the described cutting and handling process. By solving complex and interrelated optimization problems it enables an efficient production with minimal waste and without time-consuming physical reconfiguration of hard-ware or manual changes to the executable machine program.

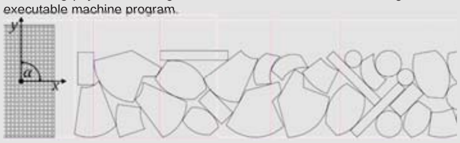

Fig. 5: Handling of cut-pieces in 3 DOFs (2 translations, 1 rotation) under constraints.

Automated supply of cut-pieces to robot cell

As soon as the drawer storage device mentioned in 3.1 is completely filled with cut-pieces, it can be driven to a receiving robot cell with a mobile logistic unit. The mobile logistic unit can be either an auto-mated guided vehicle (AGV) or a manual controlled platform (see Fig. 6). By using multiple drawer storage devices a continuous flow of cut-pieces can be provided to one or more robot cells.

Fig. 6: Drawer storage with cut-pieces on its way to a robot cell (above) and picking out of drawer storage (below)

4. Robotic pick & place process

A robotic pick and place process with a cut-piece detection camera, material friendly vacuum gripping and ultrasonic (US) fixation units then detects, grips, stacks and fixates the cut-pieces to point-welded stacks ready for consolidation with e.g. thermoforming or vacuum consolidation (see Fig. 7).

Fig. 7: Robotic pick and place end-effector.

The system layout of the end-effector is shown in Fig. 8. The vacuum is generated centrally in a Schmalz X-Pump nozzle and distributed via a *FESTO* valve cluster to the gripper units, which sit on spring followers, to have lateral stability and longitudinal draping or adapting functionality. In the current configuration a maximum of 24 grippers can be operated. The grippers sit on a aluminum frame made of *WITTE* profiles to assure fast and reproducible reconfigurations. The US horn is supplied by a US generator from Branson and moved to its place of operation by a pneumatic feeder unit sitting on *FESTO* linear axis. All systems are linked via *EtherCAT*.

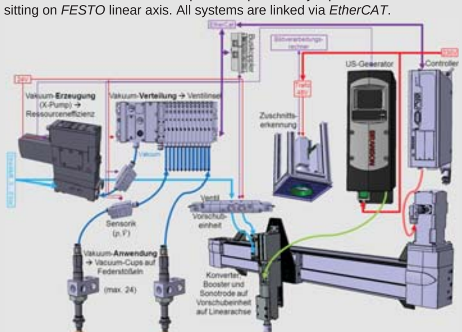

Fig. 8: System layout of the end-effector.

Automated cut-piece detection system

One major advantage achieved by the use of tailored preforms is the enhanced degree of freedom in part design. This comes with additional requirements for automation, because now there is a multitude of individual cut-pieces that causes conventional automation concepts, like aligning the cut-pieces by stoppers, to fail. A good concept is to store position and orientation of the cut-pieces after cutting. A better concept, that also compensates mechanical deviations due to machine imperfections or uncontrolled movement of cut-pieces e. g. during transport, is to equip the production system with computer vision capabilities.

Process automation

Autonomous processing requires a system architecture that is capable of generating the required actions from a generic description. A good part of this description is found in the plybook, but there is still the need for some further meta information, namely points and orientations where to grip and where to drop the cut-pieces [13], which vacuum cups to activate for gripping, where to weld the cut-pieces and the correct layup order. The plybook plus the meta information is passed to a manufacturing execution system (MES) that carries out all necessary steps (Fig. 9).

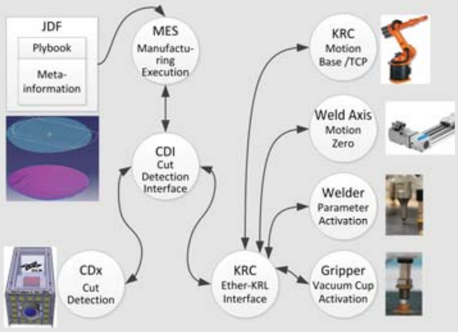

Fig. 9: Robot system layout.

The MES converts the generic description of a job definition file (JDF) to robot events like robot movements, base or tool change and I/O switching, which are passed by a cut detection specific inter-face layer to the robot interface, in our case a *KUKA* technology package for Ethernet-communication with a *KUKA KRC 4* control. The subsystems are subsequently controlled by the KRC 4, what gives the user a well-known and easy to change environment. The events generated by the MES trigger parametrized robot modules by sending command messages to the Ethernet-KRL interface's main command loop.

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